Let's build an ARTA Pressure Chamber for the calibration of microphones below 500 Hz.

An article by Alex Khenkin from Earthworks [1], a manufacturer of high-quality microphones, makes one curious to try a method of calibrating omnidirectional microphones below 500 Hz.

In the article – which is worth reading for every DIY-er who wants to know something about the calibration of microphones - the following paragraph can be found:

"Measuring very low frequencies by the substitution method is problematical because such tests require a very large anechoic space. To measure in the frequency range from zero to 500 Hz, we use a small, piston driven pressure chamber. This method is actually a primary frequency response calibration, since the pressure in a given size chamber at a given temperature depends only on the volume displaced by the driving piston. The high frequency limitation is defined by the chamber size, which should be less than 1/6 wavelength in any direction. Of course, this only works for pressure microphones (omnis)."

In the frequency range from 500 Hz to 1 kHz, Earthworks uses the substitution method in which the reference microphone is measured in front of a small cone loudspeaker mounted in the center of a large (2.4 x 2.4 m) baffle. In the frequency range from 1 kHz and higher, a tweeter is mounted on a 1.2 x 2.4 m baffle. In both measuring set ups, the response of a production microphone is measured and compared to a reference microphone's frequency response which is stored for comparison.

The lower the test frequency, the more problematic it is to construct an "infinite" baffle of a size needed to measure a plane wave free of edge reflections. Few accessible anechoic chambers exist that are suitable (or certified) for measurements below 80 Hz or so. To avoid this, Earthworks uses a small pressure chamber for calibration in the lower frequency range < 500 Hz.

The pressure chamber can be an interesting low-cost DIY project. Once the chamber is built and calibrated with a reference microphone, it is easy to measure any DUT microphone's low frequency response and sensitivity.

Functionality and construction of the pressure chamber

If the chamber's longest dimension is shorter than 1/6 to 1/8 wavelength of the upper cut-off frequency, that chamber's volume V will behave like an acoustic capacitance, C_K,

$$C_K = V / (\rho_o\, c^2) \qquad (1)$$

where $\rho_o = 1.18$ kg/m³ and $c = 344$ m/s. If the driver's membrane (cone) with area S and velocity v excites a box with the volume velocity $U = v\,S$, the interior volume has an approximately equal acoustic pressure of

$$p_k = v\,S / j\,\omega\,C_K\,. \qquad (2)$$

Membrane velocity v and displacement x are related by the expression:

$$v = j\,\omega\,x \qquad (3)$$

Substituting v from Eq. (3) into Eq. (2) we see that the sound pressure in the box is directly proportional to the membrane displacement.

$$p_k = x\,(S / C_K) \qquad (4)$$

This property is of great significance as we will show later that (in a closed box), the membrane displacement as well as the pressure inside the box are constant at low frequencies.

The dimensions of the pressure chamber (hereinafter called the chamber) are easily calculated from the requirement that the longest dimension must be no longer than1/6 to 1/8 wavelength of the maximum frequency. We establish our upper test frequency at 500 Hz and the length of the chamber will be: $\lambda = c / f = 344 / 500 = 0.688$ m $\Rightarrow$ 1/6λ to 1/8λ = 11.5 to 8.6 cm

As you can see, the dimensions of the chamber are quite manageable, and parts cost minimal.

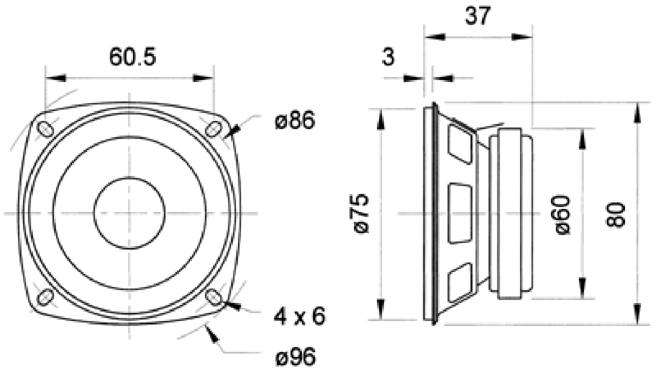


Figure 1. Visaton midrange driver FRS 8

The chamber is constructed of two MDF end plates separated by a piece of PVC waste pipe. A Visaton FRS 8 8 cm (3.3”) loudspeaker was chosen to excite the chamber. The main exterior dimensions of the chamber are shown in **Figure 2.** The remaining dimensions are not critical and can be determined from **Figures 3.1 - 3.6.**

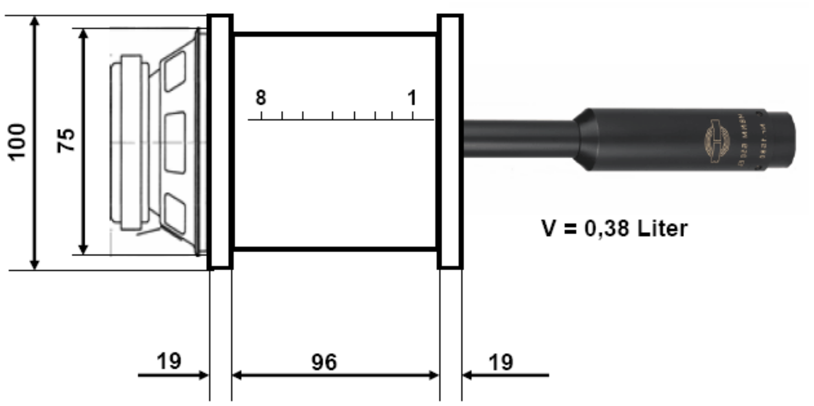


Figure 2. Dimensions of the test chamber (mm).

Quantity	Description
2	End plate:19 mm MDF, 10 x 10 cm End Plate
1	Waste pipe: 75 mm O.D., length 110 mm
4	Threaded rods M4 x 150 mm length
8	Nuts, washers, lock washers (M4)
4	M4 Nut plate (or T-nut) (to mount loudspeaker)
1	Hardwood rod, 25 mm diameter

Table 1. Test chamber parts list

Note that the PVC pipe is recessed into a 7 mm circular groove routed into each end plate resulting in a tube length of 96 mm and cylinder volume ($V=\pi r^2 h$) of 0.38 liter. The PVC pipe should be joined to the end plates with a bead of silicone-based adhesive inside the grooves and then another bead applied around the outside perimeter of the pipe for a good acoustic seal. The four threaded rods provide for a (hopefully) resonance-free enclosure.

For easier installation/removal of the loudspeaker, nut plates are installed on one of the end plates requiring only machine screws to mount the driver. The test microphone end of the chamber offers several options. If you plan to use only one microphone with say, a diameter of 12.5 mm, you can drill one 12.5 mm hole in the end plate.
For a more versatile test chamber, you can drill a stepped hole shown in **Figure 3.5.** and, using a Forstner drill bit and plug cutter, fabricate various diameter adapters shown in the same figure. The creative DIYer will 3D print the necessary adapters.

Figure 3.1 Side view of the completed chamber

Figure 3.2 Rear view of the completed chamber with Visaton FRS8 driver

Figure 3.3 Front view of the completed chamber with DUT

Figure 3.4 Front (interior) view with circular groove for pipe mounting

Figure 3.5 Front (microphone) side with hole for 25 mm rod adapter for microphones

Figure 3.6 Rear panel (driver side), exterior view showing nut plates for mounting the driver

Properties of the pressure chamber

The test microphone must be inserted in the chamber with a tightly sealed adapter. Lute, Teflon pipe tape or modeling clay can be used to affect an airtight connection. The insertion of the microphone in the chamber has the advantages that the measurement becomes quite independent of the surroundings and measurement interferences are avoided. A backward muffling of the speaker would increase this effect.

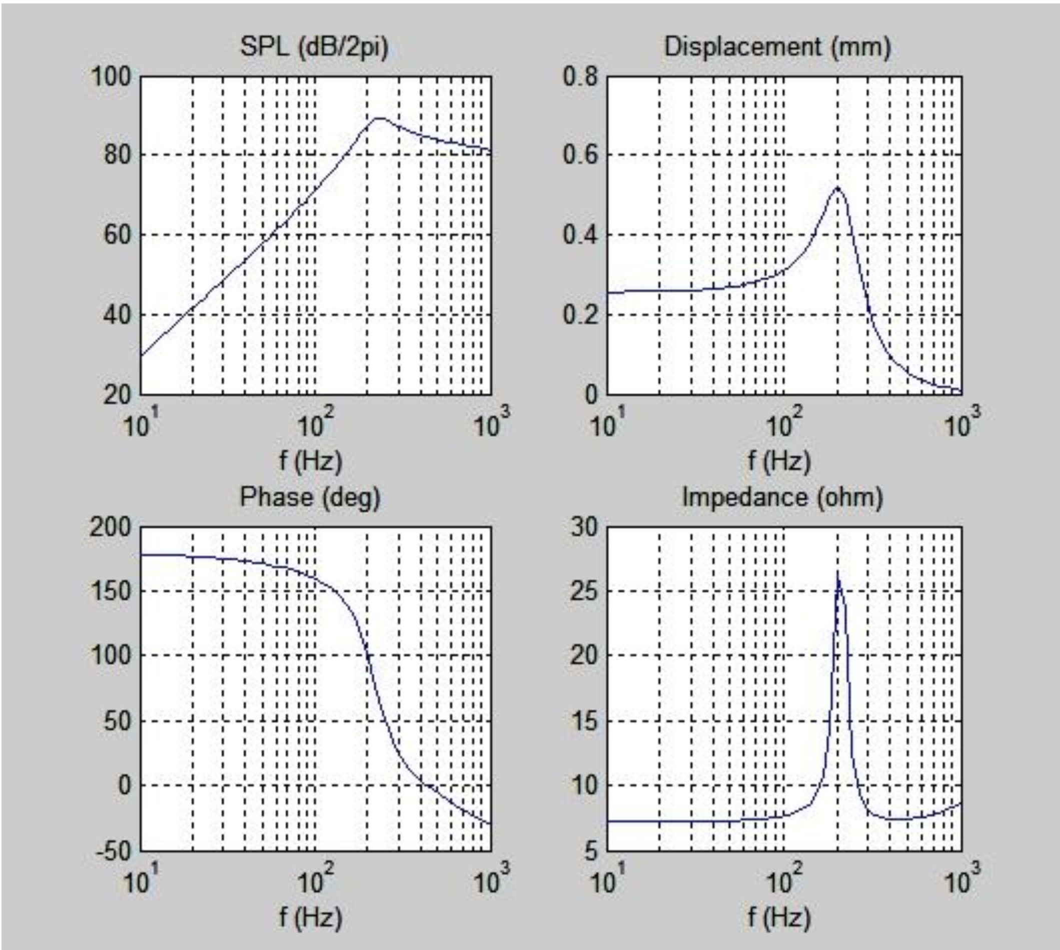


Figure 4. MATLAB simulation of the FRS 8 response in a 0.38 liter volume.

In order to prepare for the actual measurements, some preliminary tests and analyses are necessary to explain the measurement condition and sensitivity to variation of measurement parameters (microphone placement and sealing).

At first, a MATLAB simulation was carried out using the FRS 8 TS parameters and known chamber dimensions. **Figure 4** shows the characteristics of the sound pressure level (SPL), the membrane displacement, the phase, and the impedance.

Figure 5 shows the SPL of the FRS 8 inside the pressure chamber. SPL and displacement show very similar characteristics, as predicted by Eq. (4).

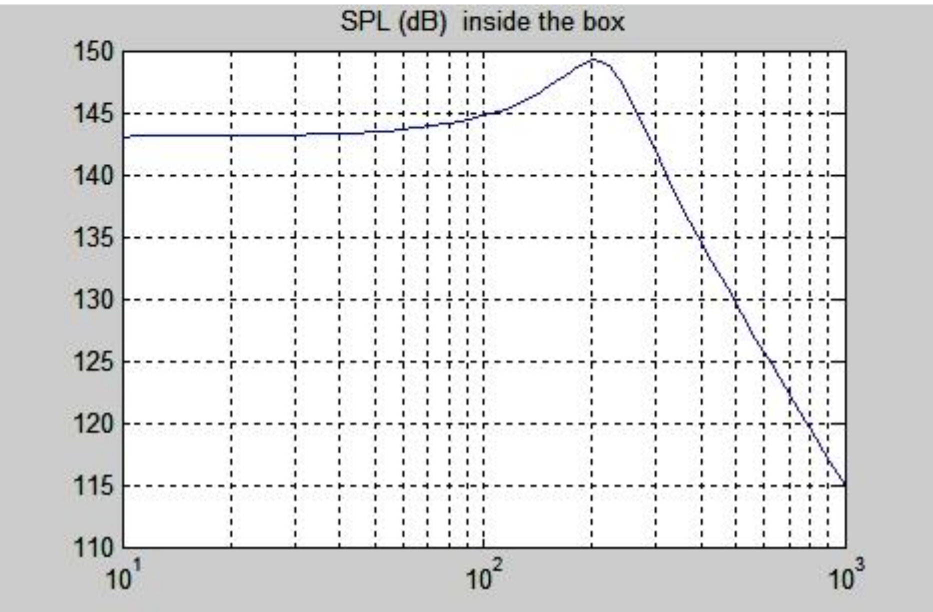


Figure 5. Characteristics of the acoustic pressure inside the measurement chamber for a 2.83V excitation (MATLAB simulation).

The acoustic pressure in the chamber for a 2.83 volt driver excitation, is remarkably high. Below the resonant frequency, it amounts to about 145 dB SPL which is far above the safe maximum acoustic pressure for popular electret microphones.

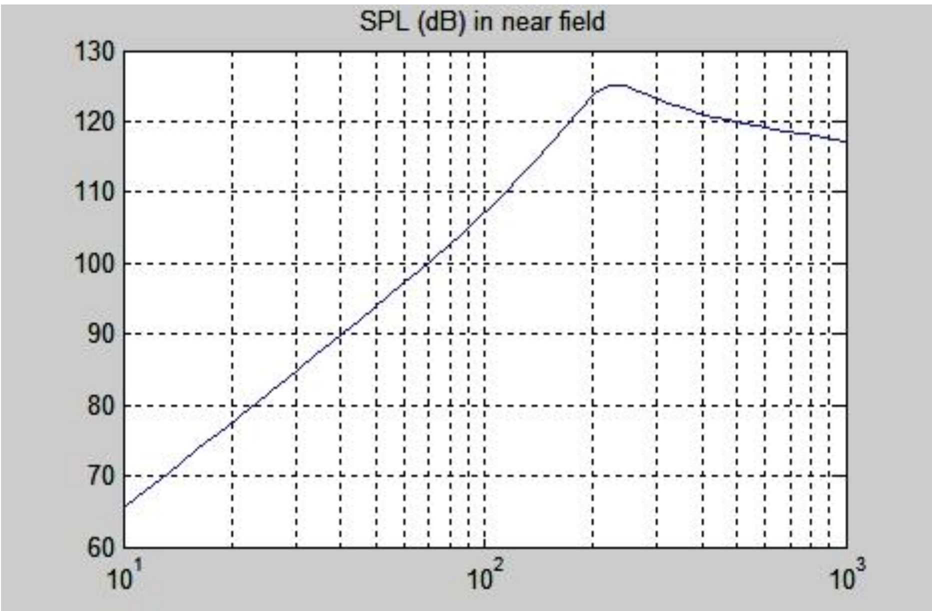


Figure 6. Characteristics of acoustic pressure in the near field. (MATLAB simulation).

The acoustic pressure characteristics were also simulated for the outer near field of the Visaton driver in order to compare the measurements later (**Figure 6**)

Measurements

As shown in **Figure 5**, a high acoustic pressure inside the chamber is to be expected. To prevent damage to the test microphone, the excitation driver voltage has to be properly adjusted to a safe voltage range.

Figure 7 shows the results of the chamber SPL vs. input voltage at 200 Hz and 1000 Hz. At 1 kHz (the usual test frequency for calibrators) the chamber needs an input voltage of only 0.107 V for an acoustic pressure of 94 dB.

In the frequency range below 200 Hz, input voltages above 0.1 V should be avoided as severe distortion as well as damage to the microphone can occur. In this frequency range an input voltage of about 0.01 volt RMS will generate a SPL of 94 dB.

In the second step, the near field frequency response of the FRS 8 was determined. Due to the assembly, the sound pressure could only be measured just behind the magnet (see **Figure 8**). In comparison to the simulation, it had about a 15 dB lower SPL which could be a result of a different measurement setup. A controlled measurement with an FRS 8 on an open baffle confirmed the assumption. The difference of the pressure between front and back side in the near field is about 13.9 dB at 200 Hz.

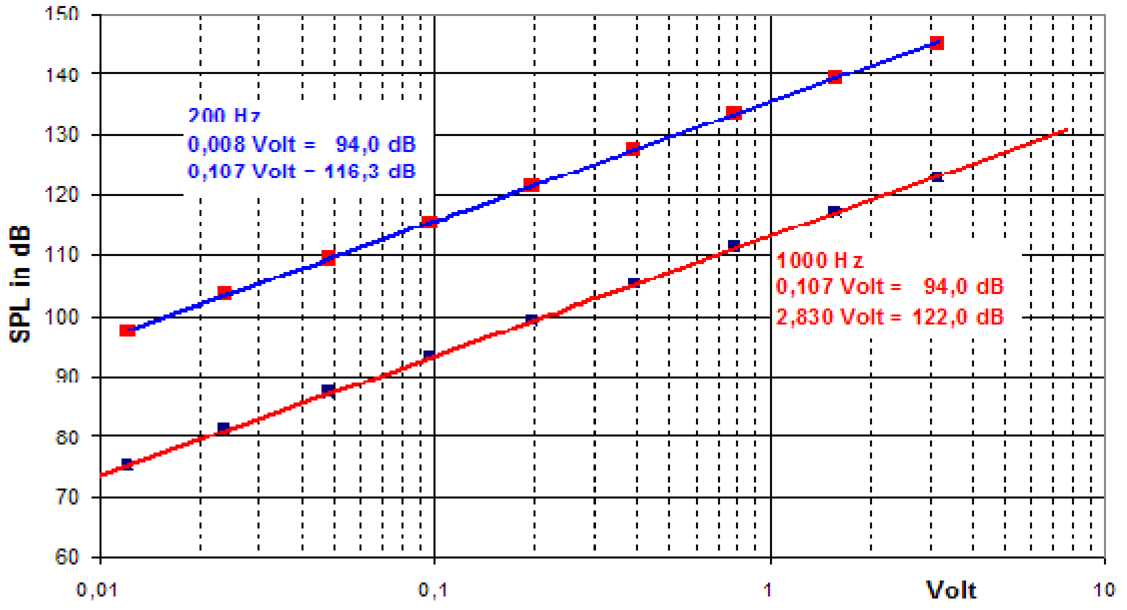


Figure 7. Sensitivity of the test chamber at 200 Hz & 1 kHz (SPL vs. input voltage).

The measured data shown in Figure 7 are valid for the chamber of the dimensions listed. If the DIYer follows the same dimensions, construction and uses the same driver, it should be possible to reproduce the same results as in this Application Note with only minor differences.

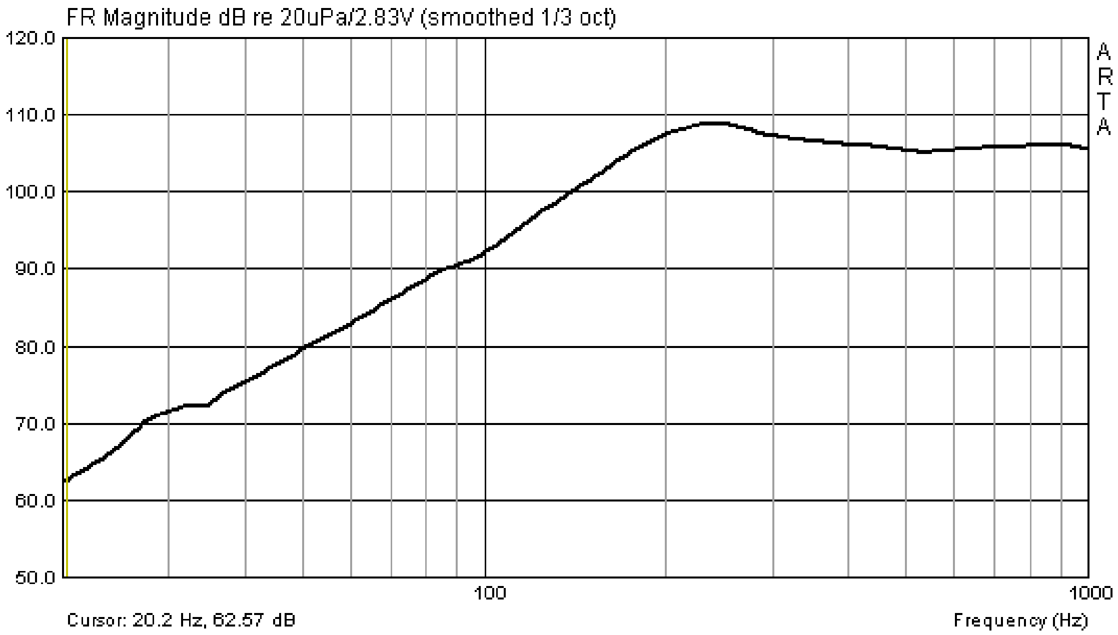


Figure 8. Characteristic of the acoustic pressure in the near field (microphone placed near the center of the magnet) of the Visaton FRS 8.

Microphone location analysis

Next, the influence of the position of the microphone in the chamber was tested. The frequency response of a Panasonic WM 60 capsule was measured at 8 different microphone positions in the frequency range from 5 Hz to 1 kHz. Position 1 is located 1 cm from the MDF-plate toward the Visaton driver. Other positions are each 1 cm closer to the driver. Results are shown in **Figure 9.** (Compare with the simulation of **Figure 5**).

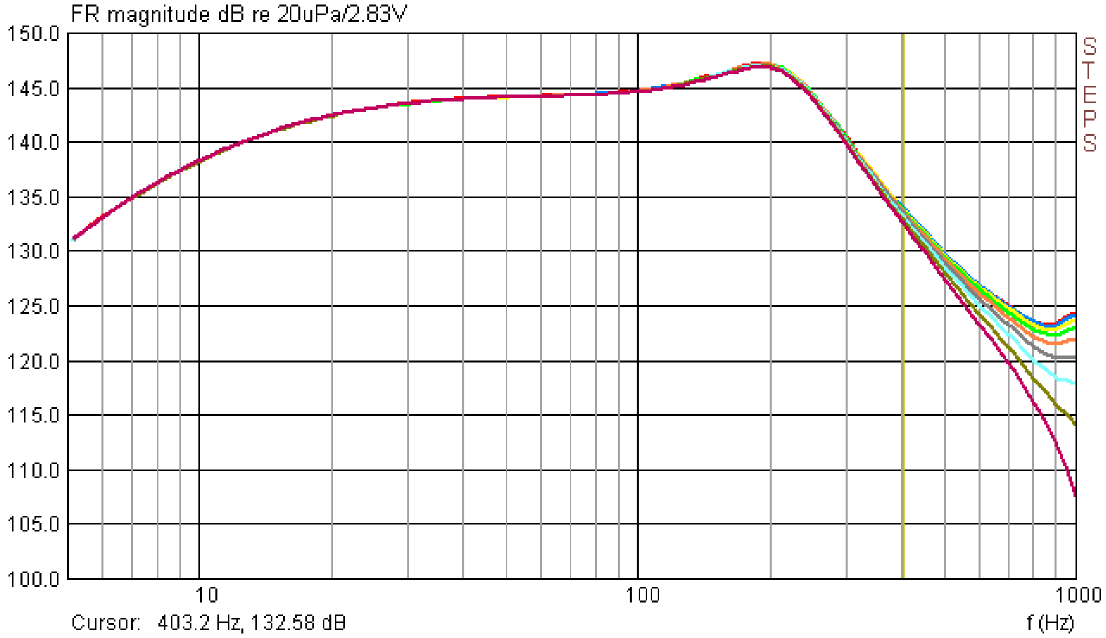


Figure 9. Magnitude deviation vs. WM 60 microphone position.

First, it is clear that measurements above 20 Hz match quite well with the MATLAB simulation. The absolute pressure level as well as the frequency response characteristics are well-duplicated by the simulation.

Second, it can be seen that the influence of the position of the microphone becomes significant above 400 Hz. The analysis of the two most differing measurement points can be seen in table 2.

Position	100 Hz	200 Hz	300 Hz	400 Hz	500 Hz
Pos 1 cm	144.73	147.12	140.25	134.00	129.62
Pos 8 cm	144.65	146.82	139.48	132.58	127.21
SPL difference (dB)	0.08	0.30	0.77	1.42	2.41

Table 2. Dependence of the measurement position

If the position of the microphone is held constant (± 1 cm) it can be assumed that the difference will always be less than 1 dB at 500 Hz.

Acoustic Seal Importance

A third parameter, the influence of the seal of the microphone to the chamber was investigated. **Figure 10** shows the results.

The blue curve shows the frequency response of the test microphone adapter securely sealed with lute; the red curve is the response for a measurement using an adapter for the microphone but with less sealing (small crack); and the black curve is the response for a measurement without an adapter and no sealing (bigger crack).

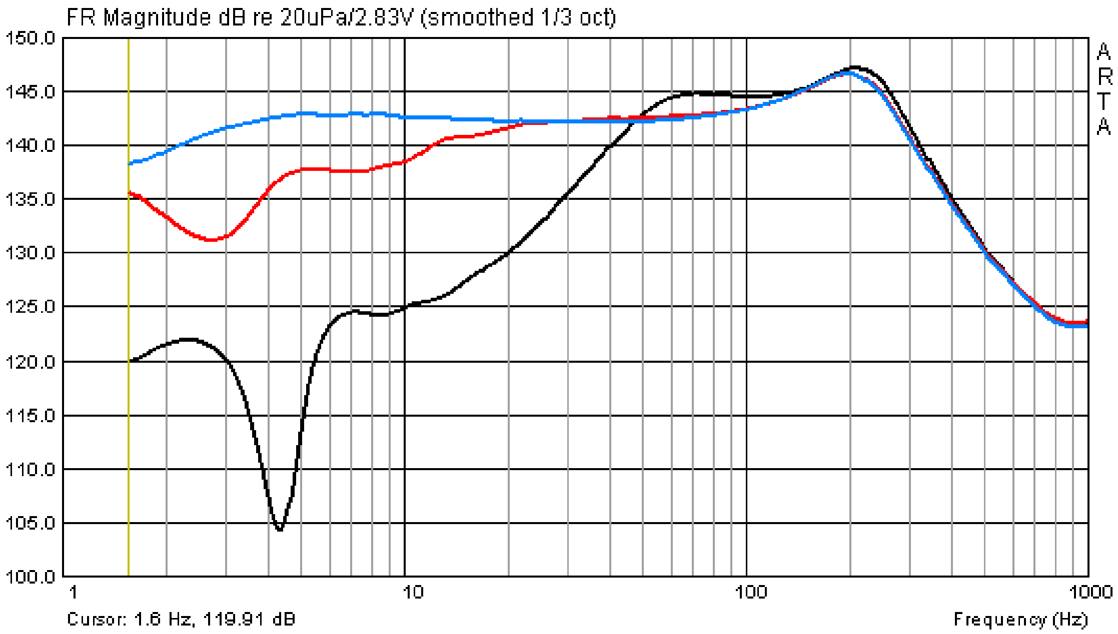
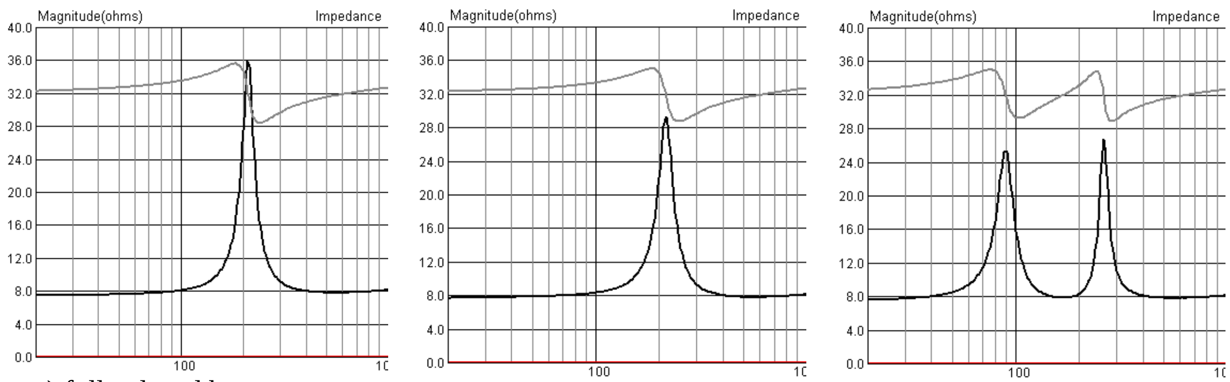


Figure 10. Frequency response showing dependency of chamber sealing with MK 221microphone.

What is immediately obvious is that the chamber must be well sealed with the microphone in place or the measurement will be erroneous. Sealing the test chamber should be no problem as lute, clay or Teflon pipe tape along with some trial and error experiments will quickly show what is effective.

The leakage can be easily detected by noting either a change of the frequency response of the microphone or the Visaton loudspeaker impedance curve. **Figure 11a)** shows the impedance curve for a fully sealed chamber; **Figure 11b)** shows the impedance curve for the chamber with small opening around microphone adapter, and **Figure 11c)** shows impedance curve for the chamber with an open 13 mm adapter.



a) fully closed box
b) with small opening
c) with larger opening

Figure 11. Effect of the opening of the chamber on the loudspeaker impedance curve.

Calibration Measurements

The calibration of microphone frequency response has several steps:

1) Measure in-box frequency response of reference microphone.
2) Scale the reference response so that response at 200 Hz represent reference 0 dB, and save in textual file. Remember the scaling term.

   (Instead of 200 Hz you may choose some other frequency from microphone pass-band range.)
3) Enter the saved reference response in ARTA or STEP as frequency response compensation file.
4) Measure the test microphone frequency response with a frequency compensation turned on.
5) Scale the frequency response to show 0 dB at 200 Hz and save it in a textual file.
6) Optionally, to get sensitivity of test microphone, add difference in scaling of test and reference microphone to sensitivity of reference microphone

For the calibration measurements of the test chamber, the Microtech Gefell MK-221 was used as the reference microphone.

Technische Daten/Specifications MK 221

21.31 92.58	PTB-Zulassung-Nr. zur amtlichen Eichung	CE

Wandlertyp Transducer type	Kapazitiver Druckempfänger Capacitive pressure transducer
*Frequenzbereich des Freifeldübertragungsmaßes *Frequency range free-field response	3,5 Hz ... 20 kHz (± 2 dB)
*Feld-Leerlauf-Übertragungsfaktor/Sensitivity	50 mV/Pa
Grenzschalldruckpegel für 3 % Klirrfaktor bei 1 kHz Max. SPL for THD ≤ 3 % at 1 kHz	146 dB

Figure 12. Extract of the specifications of the reference microphone.

From the specification sheet of the MK 221 microphone, we read that the frequency range is specified from 3.5 Hz to 20 kHz ± 2 dB. The maximum acoustic pressure of 146 dB @ 3% THD gives some reserve compared to the usual DIY electret microphones.

Figure 13 shows the results of measuring the frequency response inside the chamber using STEPS and the MK 221 microphone. Note that the measurement is almost identical with the simulation in this case.

Theoretically, for a well-sealed enclosure, the calibration of a microphone can be completed without the comparison to a reference microphone. Instead of reference microphone measured response data we can use MATLAB simulation data.

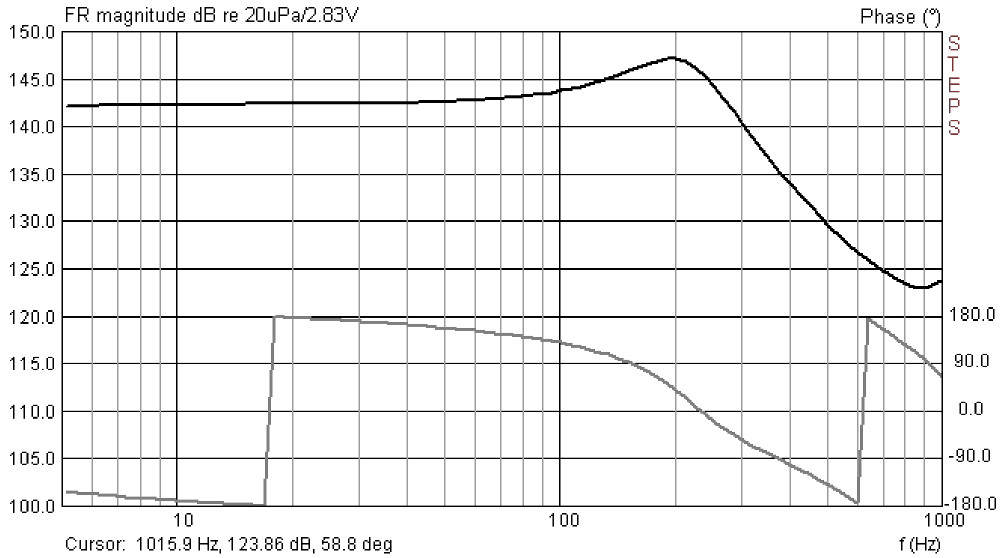


Figure 13. Reference frequency response in the measurement chamber

For comparison to the reference frequency response, the following microphones were used:

- MB 550
- 2 Sennheiser KE4-211 (different sized capsule)
- Monacor ECM-2000
- Panasonic WM 60

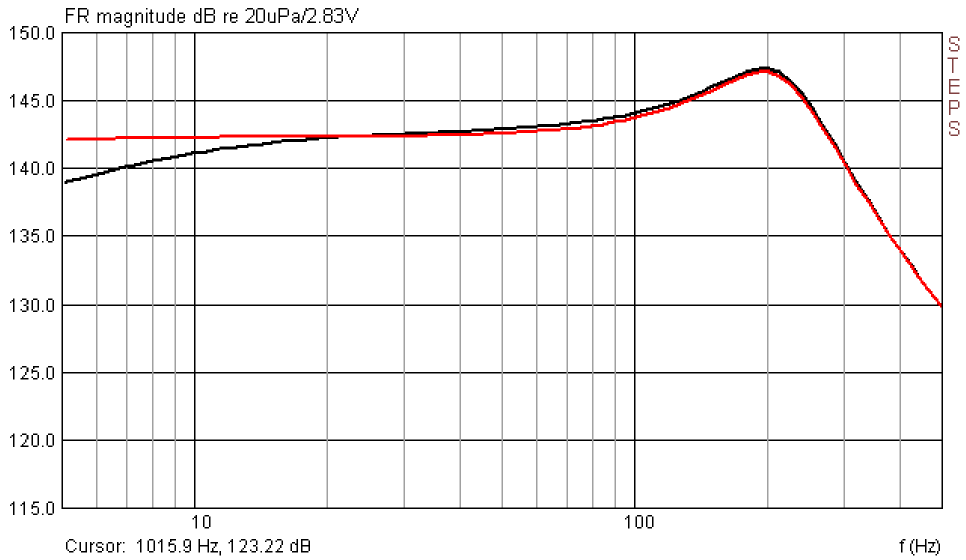


Figure 14. Response of MB 550 microphone (black) and the reference frequency response (red) - scaled to show difference from reference pressure level.

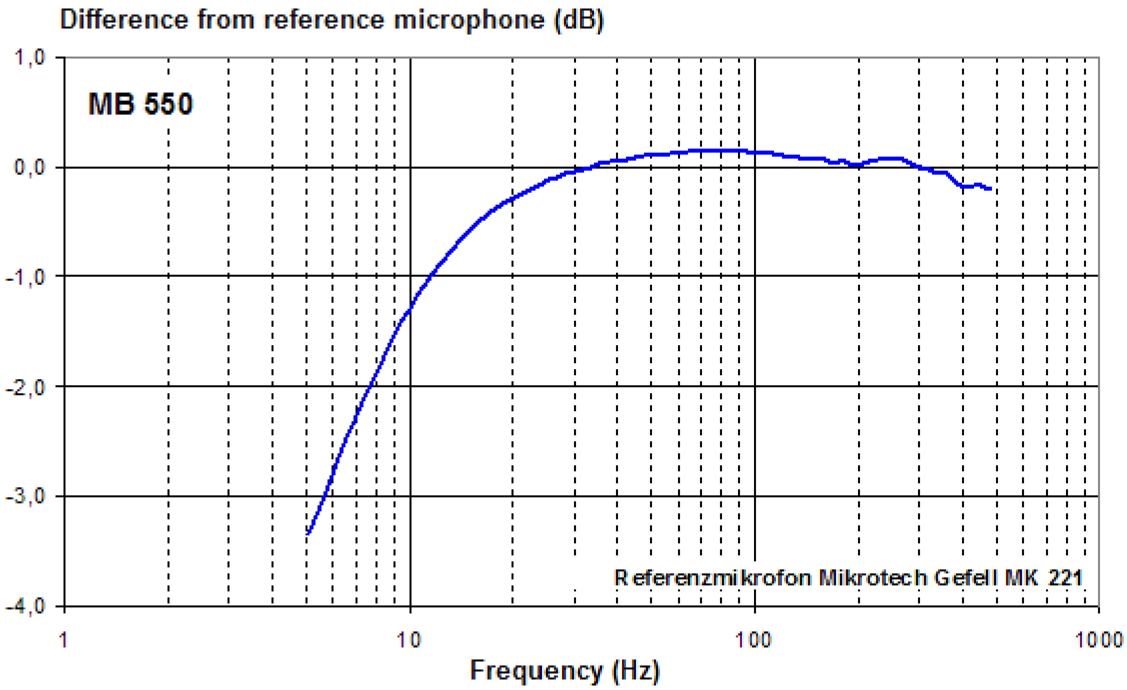


Figure 15. MB 550 - difference from the reference microphone frequency response.

Figure 15 shows the result for the microphone MB 550 determined with STEPS. The results of the remaining microphones are combined in **Figure 16.**

It becomes obvious that noticeable deviations between DIY-microphones below 50 Hz are common. Even a comparatively high-quality microphone such as the KE4-211 does not guarantee that deviations from the specification are negligible.

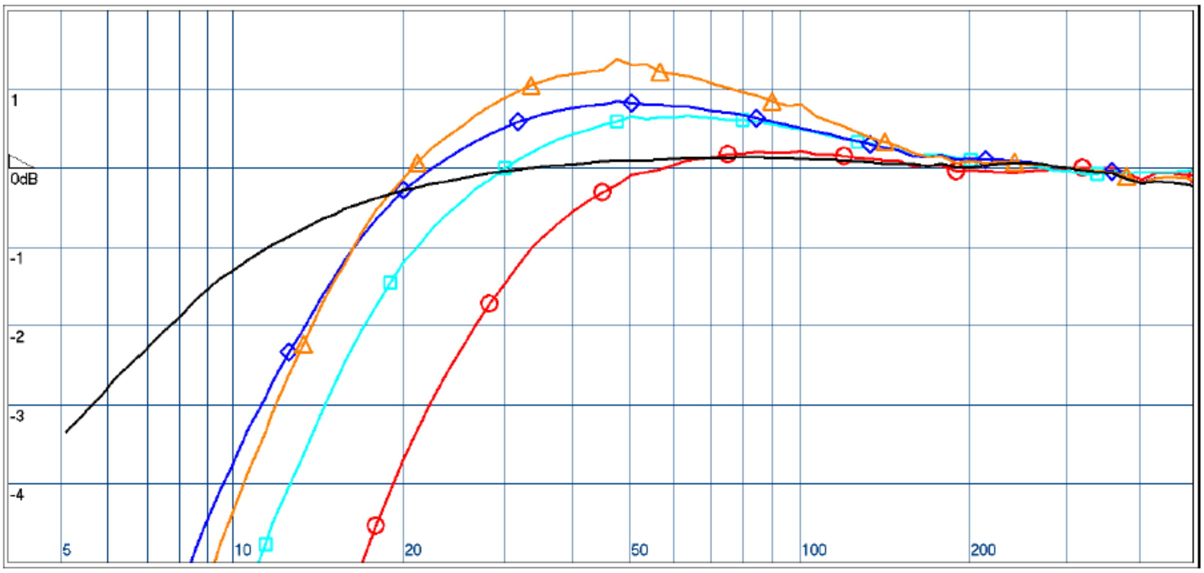


Figure 16. Calibrated frequency response of the tested microphones: black (MB 550), red (KE4-221, Nr1L), cyan (KE4-211, Nr2K), blue (ECM 2000), orange (Panasonic WM 60).

Conclusion

With the ARTA Pressure Chamber it is easy to calibrate microphone frequency response up to 500 Hz. Optimally, one should initially calibrate the chamber with a reference microphone and save the data as a STEPS or ARTA calibration file. Without a reference microphone, calibration should be possible based upon the MATLAB simulation.

The cost for constructing the chamber is low, so there is no reason not to try this interesting and useful experiment.

Heinrich Weber and Ivo Mateljan
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Literature

[1] Alex Khenkin, *How Earthworks Measures Microphones*, published at:
http://recordinghacks.com/pdf/earthworks/how-earthworks-measures-mics.pdf

Appendix I - MATLAB script for the loudspeaker closed box response

```
clear
echo off
j=sqrt(-1);
f = logspace(log10(10),3,50);
n = max(size(f));
w = 2*pi*f;
c=344; r0=1.18;
%------------------ start user Input
%input voltage
e=2.83;

%box volume
Vol = 0.39e-3;

%distance 1m
r=1;

%driver parameters (i.e. FRS 8)
Re = 7.2;
Le=  0.85e-3;
fs=120;
Bl = 3.2;
Sm = 31e-4;
Vas = 0.91e-3;
Qt = 1.04;
Qe = 1.32;
Qm = 4.85;
%----------------------- end user input

Cm = Vas/(r0*c^2*Sm^2);
Mm=1/((2*pi*fs)^2*Cm);
Rm = 1/((2*pi*fs)*Qm*Cm);
a=sqrt(Sm/pi);
ws=2*pi*fs;

pout = ones(1,n);
pin = ones(1,n);
pnf = ones(1,n);
xuk=ones(1,n);
zul=ones(1,n);

%radiation impedance constants
ra1 = 0.1404*r0*c/a^2;
ra2 = r0*c/(pi*a^2);
ma1 = 8*r0/(3*pi^2*a);
ca1 = 5.94*a^3/(r0*c^2);

% box constants
Cb=Vol/(r0*c^2);   %box compliance
Mao=0.85*a*r0/Sm;  %membrane air mass loading

for k=1:n
        ww = w(k);  jw = j*ww;
        % radiation impedance
        z1 = jw*ma1;         z2 =1/(jw*ca1);
        z3=z2*ra1/(ra1+z2); z3= z3+ra2;
        Zar=1/(1/z1+1/z3);

        %box analogous circuit
        Ze= Re + jw*Le;
        Zm= Rm + jw*Mm +1/(jw*Cm);
        A11 = Ze*Sm/Bl;
```

```
        A12 = Ze*Zm/(Sm*Bl) + Bl/Sm;
        A21 = Sm/Bl;
        A22 = Zm/(Sm*Bl);
        Zak =Zar + jw*Mao + 1/(jw*Cb);
        zul(k)= (A11*Zak+A12)/(A21*Zak+A22);
            %volume velocity
        U1 = e/(A11*Zak+A12);
        %displacement
        xuk(k) = (U1/Sm)/jw;
        %presure at distance r (infinite baffle mounted)
        pout(k) = jw*r0*U1/(2*pi*r);
            %pressure inside the box
        pin(k) = U1/(jw*Cb);
        %near field pressure
        kk = ww*a/2/c;
        pnf(k)= jw*r0*(U1/(a*pi))*sin(kk)/kk;

end

%level in far filed (db/1m)
pdb= 20*log10(abs(pout)/2e-5);

%level in the box
pudb= 20*log10(abs(pin)/2e-5);

%level in the near field
pnfdb= 20*log10(abs(pnf)/2e-5);

semilogx(f,pudb),title('SPL (dB)  inside the box'),grid,pause
semilogx(f,pnfdb),title('SPL (dB) in near field'),grid,pause

subplot(221);
echo off;
semilogx(f,pdb),title('SPL (dB/2pi)'),grid;
xlabel('f (Hz)');
subplot(222);
semilogx(f,abs(xuk)*1000),title('Displacement (mm) '),grid;
xlabel('f (Hz)');
subplot(223);
semilogx(f,angle(pout)*180/pi),title('Phase (deg) '),grid;
xlabel('f (Hz)');
subplot(224);
semilogx(f,abs(zul)),title('Impedance (ohm)'),grid;
xlabel('f (Hz)'), pause;
subplot;
```

Appendix II - Measuring the distortion of microphones

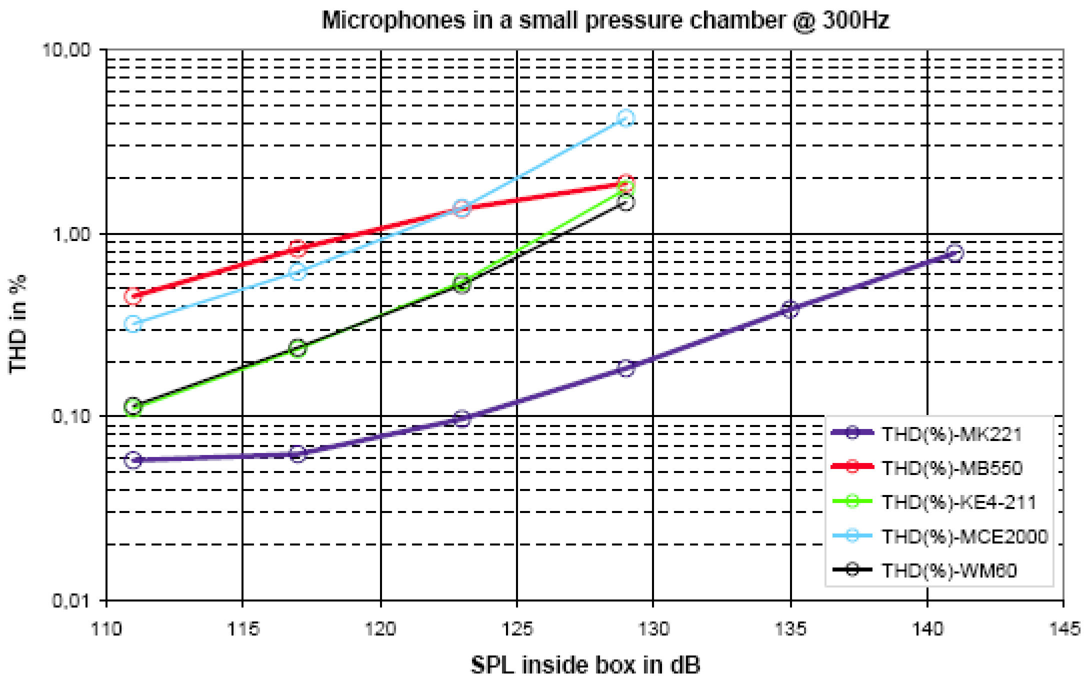

Figure A1. Relative comparison of distortion of several microphones at 300 Hz.